

A Supersymmetric Model with an Extra U(1) Gauge Symmetry

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Abstract

In the standard model the proton is protected from decay naturally by gauge symmetries, whereas in the ordinary minimal supersymmetric standard model an ad hoc discrete symmetry is imposed for the proton stability. We present a new supersymmetric model in which the proton decay is forbidden by an extra U(1) gauge symmetry. Particle contents are necessarily increased to be free from anomalies, incorporating right-handed neutrinos. Both Dirac and Majorana masses are generated for neutrinos, yielding non-vanishing but small masses. The superpotential consists only of trilinear couplings and the mass parameter μ of the minimal model is induced by spontaneous breaking of the U(1) symmetry.

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Extending the standard model (SM) by supersymmetry [1], though considered to be promising for physics above the electroweak energy scale, is confronted with a problem of the proton stability. Among the possible interactions allowed by the gauge symmetries of the SM and renormalizability, those which violate baryon-number or lepton-number conservation are included, leading to an unacceptably fast decay of the proton. For forbidding these interactions, an ad hoc discrete symmetry is usually imposed on supersymmetric models through R parity, as on the minimal supersymmetric standard model (MSSM). On the other hand, in the SM, baryon and lepton numbers are conserved merely as a consequence of gauge symmetries. Some more fundamental reason for the proton stability should exist also in the supersymmetric standard model.

Neutrino masses also pose a potential problem for the MSSM. Experiments for atmospheric and solar neutrinos, such as at the Super-Kamiokande [2], suggest non-vanishing masses for the neutrinos. Theoretically, Yukawa couplings which generate their Dirac masses can be included naively by incorporating the superfields of right-handed neutrinos. However, these superfields are inert for the transformations of the SM gauge groups and thus their *raison d'être* is vague. Furthermore, if the extreme lightness of the neutrinos is explained by large Majorana masses for their right-handed components, new mass parameters of unknown origin have to be introduced.

Another potential problem is raised by the linear coupling of the Higgs superfields contained in the superpotential of the MSSM. Since the mass parameter μ of this coupling enters into the scalar potential which determines $SU(2) \times U(1)$ symmetry breaking, its magnitude should be of the electroweak scale. Assuming the model coupled to $N = 1$ supergravity, the other mass parameters in the scalar potential are traced back to supersymmetry-soft-breaking terms and thus related to the gravitino mass which can be taken as the electroweak scale. On the other hand, various mechanisms have been proposed to generate the μ parameter, although its origin is still controversial [3].

Aiming at providing natural and consistent solutions for the above problems, in this letter, we propose a new supersymmetric standard model, based on the gauge symmetries

with an extra $U(1)$ group and $N = 1$ supergravity. It is plausible that the proton stability is guaranteed by a gauge symmetry. In particular, one of the simplest possibilities is by $U(1)$ [4–8]. We present a $U(1)$ gauge symmetry which conserves baryon number but allows lepton-number violation, sufficient for the proton stability. Particle contents are necessarily increased in order to be free from gauge and trace anomalies, and then incorporate right-handed neutrinos. Also included is a scalar field which has a non-vanishing vacuum expectation value (v.e.v.) and breaks the $U(1)$ gauge symmetry. This v.e.v. induces Majorana masses for the right-handed neutrinos and an effective μ parameter for the Higgs linear coupling. The $U(1)$ gauge symmetry predicts a new neutral gauge boson, for which non-trivial constraints have been obtained from experiments. We show that these constraints can be satisfied without fine-tuning much model parameters. A natural scale of this model becomes of order 1 TeV, which could account for the smallness of the electric dipole moments (EDMs) of the neutron and the electron, another problem in general supersymmetric models.

The model consists of the left-handed chiral superfields listed in Table I, where shown are their quantum numbers under $SU(3)$, $SU(2)$, $U(1)$, and $U'(1)$ gauge transformations. The extra $U(1)$ group is denoted by $U'(1)$. The index i stands for the generation. The $U'(1)$ charges have been normalized as $\text{Tr}(Y^2)=\text{Tr}(Y'^2)$, Y and Y' being respectively hypercharge and $U'(1)$ charge generators. The generators Y and Y' are orthogonal, $\text{Tr}(YY')=0$. The gauge anomalies and the trace anomalies are canceled in each generation. New superfields which are not contained in the MSSM are $SU(3)$ triplets K^i and K^{ci} and $SU(3)\times SU(2)\times U(1)$ singlets N^{ci} and S^i . The superfields for right-handed neutrinos are denoted by N^{ci} . In addition, there exist $SU(2)$ doublets H_1^i and H_2^i in each generation, some or all of which assume $SU(2)\times U(1)$ symmetry breaking as Higgs fields. In respect of the quantum numbers for the SM gauge groups, the particle contents resemble those of the extra- $U(1)$ model based on the fundamental representation of the E_6 group. The difference is in hypercharge assignment to the new colored superfields, which is necessary to protecting the proton from decay by introducing an extra $U(1)$ symmetry [6,7]. In such an E_6 model an additional discrete symmetry has to be imposed for forbidding the proton decay.

The superpotential is given by

$$\begin{aligned}
W = & \eta_d^{ijk} H_1^i Q^j D^{ck} + \eta_u^{ijk} H_2^i Q^j U^{ck} + \eta_e^{ijk} H_1^i L^j E^{ck} + \eta_\nu^{ijk} H_2^i L^j N^{ck} \\
& + \lambda_N^{ijk} S^i N^{cj} N^{ck} + \lambda_H^{ijk} S^i H_1^j H_2^k + \lambda_K^{ijk} S^i K^j K^{ck},
\end{aligned} \tag{1}$$

where contraction of group indices is understood. This superpotential contains all the terms consistent with gauge symmetries and renormalizability. The interactions which would violate baryon- or lepton-number conservation in the MSSM, i.e. $D^c D^c U^c$, $L Q D^c$, $L L E^c$, $H_1 H_1 E^c$, and $L H_2$, are not allowed. In fact, baryon number is conserved while lepton number is not. The lowest dimension operators for baryon-number violation are given by the D terms of $Q Q U^{c*} E^{c*}$, $Q Q D^{c*} N^{c*}$, and $Q U^{c*} D^{c*} L$, which have dimension 6. Therefore, the proton decay is suppressed at least by a huge mass to the second power. If this mass is of order the energy scale of grand unified theories (GUTs) or larger, the proton becomes adequately stable. The couplings in Eq. (1) are all cubic, and there is no dimensionful parameter. The terms $H_1 Q D^c$, $H_2 Q U^c$, $H_1 L E^c$, and $H_2 L N^c$ yield Dirac masses for quarks and leptons including neutrinos. Through a non-vanishing v.e.v. of the scalar component of S , the term $S N^c N^c$ generates a Majorana mass for the right-handed neutrino and the term $S H_1 H_2$ serves as the linear coupling of the Higgs superfields in the MSSM. The term $S K K^c$ induces a mass for the fermion components of K and K^c .

The model is coupled to $N = 1$ supergravity, which is spontaneously broken in a hidden sector at the Planck mass scale. Below the GUT scale the Lagrangian of the observable sector consists of a supersymmetric part and a supersymmetry-soft-breaking part prescribed by gauge symmetries and superpotential. The soft-breaking part contains mass terms for scalar bosons and gauge fermions, and trilinear couplings for scalar bosons.

We now examine the vacuum structure of this model. The $SU(2) \times U(1) \times U'(1)$ gauge symmetry can be spontaneously broken by non-vanishing v.e.v.s for the scalar components of H_1^i , H_2^i , and S^i . Since it is too complicated to discuss the vacuum with all of them being taken into account, we assume only one set of them to have non-vanishing v.e.v.s, for simplicity. The scalar potential is then given by

$$\begin{aligned}
V = & \frac{1}{8}g_2^2 \left(|H_1|^2 + |H_2|^2 \right)^2 + \frac{1}{8}g_1^2 \left(|H_1|^2 - |H_2|^2 \right)^2 \\
& + \frac{1}{72}g'^2 \left(4|H_1|^2 + |H_2|^2 - 5|S|^2 \right)^2 \\
& - \left(\frac{1}{2}g_2^2 - |\lambda_H|^2 \right) |H_1 H_2|^2 + |\lambda_H|^2 \left(|H_1|^2 + |H_2|^2 \right) |S|^2 \\
& + \left(B_H \lambda_H m_{3/2} S H_1 H_2 + \text{H.c.} \right) + M_{H_1}^2 |H_1|^2 + M_{H_2}^2 |H_2|^2 + M_S^2 |S|^2,
\end{aligned} \tag{2}$$

where $m_{3/2}$ denotes the gravitino mass, B_H being a dimensionless constant, and $M_{H_1}^2$, $M_{H_2}^2$, and M_S^2 represent mass-squared parameters. The gauge coupling constants for SU(2), U(1), and U'(1) are denoted by g_2 , g_1 , and g' , respectively. We have adopted the same notation for the superfields and their scalar components. Differently from the MSSM, there is no D-flat direction where quartic couplings of Higgs fields are absent, and the potential has a stable minimum irrespectively of the supersymmetry-soft-breaking terms. If the condition $g_2^2 > 2|\lambda_H|^2$ is satisfied, electric charge is conserved. Redefining the global phases of the fields so as to give $B_H \lambda_H = -|B_H \lambda_H|$, the v.e.v.s v_1 , v_2 , and v_s of the neutral components of H_1 , H_2 , and S , respectively, become real and non-negative. These values are determined by extremum conditions $\partial V / \partial v_1 = 0$, $\partial V / \partial v_2 = 0$, and $\partial V / \partial v_s = 0$. It turns out that the solution of these simultaneous equations with v_1 , v_2 , and v_s all non-vanishing is unique, if exists. The true vacuum is either at such a point or a point on the boundary $v_1 v_2 v_s = 0$, which can be identified by comparing the potential energies of those points.

On the v.e.v.s, there exist experimental constraints. The W boson mass has been measured precisely. Furthermore, there appear two massive neutral gauge bosons Z_1 and Z_2 ($M_{Z_1} < M_{Z_2}$) as mass eigenstates of the Z boson for SU(2)×U(1) and the Z' boson for U'(1). The measured mass of Z for the SM should be taken as the mass of Z_1 ; the lower bound on the mass of Z_2 is given by $M_{Z_2} \gtrsim 600$ GeV [9]; and the mixing between Z and Z' should be sufficiently small, roughly given by $A_{ZZ'}^2 / A_{ZZ} A_{Z'Z'} (\equiv R) \lesssim 10^{-3}$, where A_{ZZ} , $A_{Z'Z'}$, and $A_{ZZ'}$ represent the elements of the mass-squared matrix A for Z and Z' , according to analyses of various measurements for electroweak parameters [10]. These constraints require in some degree non-trivial differences of scale between the v.e.v.s.

The scalar potential in Eq. (2) gives a plausible vacuum under certain ranges of parame-

ter values, which is seen by numerical analyses. The above constraints on the v.e.v.s can be generally satisfied if the typical scale of the mass parameters in the potential is larger than 1 TeV. However, as the mass scale increases, more fine-tuning becomes inevitable to obtain the hierarchy of the v.e.v.s. Therefore, it would be natural to consider the mass scale to be of order 1 TeV. We present an example of the vacuum in Tables II and III. In Table II the values of the parameters in the potential are shown, where the gauge coupling constant for $U'(1)$ is taken for $g' = g_1$. The v.e.v.s, M_{Z_2} , R , and the masses of the physical Higgs bosons are shown in Table III, where H^0 , A^0 , and H^\pm stand for the neutral scalar, neutral pseudoscalar, and charged Higgs bosons, respectively. The Higgs boson masses have been calculated, assuming for definiteness that the Higgs fields H_1 , H_2 , S form mass eigenstates by themselves without mixing with the other fields of H_1^i , H_2^i , and S^i . In this case the neutral Higgs bosons do not mediate interactions of flavor-changing neutral current, thus causing no effect on K^0 - \bar{K}^0 mixing. As in other supersymmetric models, one Higgs boson is light. This mass could increase non-negligibly if one-loop corrections are incorporated. If the v.e.v.s are set for $v_2/v_1 = 2$, the mixing parameter R vanishes.

In Tables II and III, the dimensionless parameters have reasonable values, and the differences between the mass parameters are at most of one order of magnitude, suggesting that only mild fine-tuning is required. Scalar fields are considered to have supersymmetry-soft-breaking masses of order the gravitino mass $m_{3/2}$ at around the GUT scale. Then, $M_{H_2}^2$ and M_S^2 receive large negative contributions through quantum corrections at the electroweak scale, owing to the couplings $H_2 Q^3 U^{c3}$ and $S K^j K^{ck}$ with large coefficients. Therefore, a small value for $M_{H_2}^2$ and a negative value for M_S^2 , as shown in this example, are likely to occur [11]. On the other hand, quantum corrections to $M_{H_1}^2$ are not so large, and its value should remain around $m_{3/2}^2$. Similarly, the scalar particles other than the Higgs bosons have masses of order the gravitino mass. Although the masses-squared for the scalar components of K^i and K^{ci} receive non-negligible negative contributions from the D-term of $U'(1)$, the positive contributions from the soft-breaking terms dominate over, keeping $SU(3)$ symmetry unbroken. The scalar components of N^{ci} also do not have non-vanishing v.e.v.s.

The neutrino masses and the effective μ parameter are generated in realistic ranges. For $\lambda_N = 0.1$, taking a neutrino Dirac mass for the same as the electron mass, the lighter mass eigenvalue becomes about 0.5 eV, which varies in proportion to the square of the Dirac mass. The effective μ parameter is given by $\lambda_H v_s / \sqrt{2}$, leading to $|\mu| \approx 240$ GeV. Assuming that the gauge fermions for SU(2), U(1), and U'(1) receive masses of order 100 GeV from the soft-breaking terms, the masses of the lighter chargino and the lightest neutralino become of order 100 GeV.

The numerical analyses provide, as a byproduct, an explanation for a problem on the EDMs of the neutron and the electron. If one assumes the squark and slepton masses of order 100 GeV and the CP -violating phases intrinsic in supersymmetric models unsuppressed, these EDMs are predicted to be much larger than their experimental upper bounds. However, in this model, the lower bound on the Z_2 boson mass implies that a natural scale for soft-breaking masses of scalar fields are of order 1 TeV. Consequently, the squarks and sleptons have masses of this order of magnitude. Then, the constraints from the EDMs become theoretically amenable and the CP -violating phases need not be fine-tuned very small [12]. If these phases are not suppressed, sizable CP violation is expected to occur in some reactions at the energy scale of order 1 TeV. In particular, since lepton number is also violated, certain reactions could involve both CP violation and lepton-number violation. For instance, the Higgs boson which is mainly composed of S can decay into both $\nu_R \nu_R$ and $\bar{\nu}_R \bar{\nu}_R$, whose branching ratios could have different values. Such reactions may lead to a non-vanishing lepton number in the universe at around its electroweak phase transition. The baryon asymmetry of the universe could then be generated by converting the net lepton number through the sphaleron process.

In this model, a Dirac fermion which is composed of the fermion components of K and K^c becomes stable, having both color and electric charges. Its mass is given by $\lambda_K v_s / \sqrt{2}$, which is of order 100 GeV – 1 TeV. The particle could thus be detectable in near-future experiments. On the other hand, such a stable particle may also be explored by non-accelerator experiments, e.g. search for anomalous nuclei in seawater, provided that its relic

density in the universe is not very small. In fact, a purely perturbative calculation for the pair annihilation of this particle leads to a density which may be inconsistent with constraints from such experiments. However, the annihilation cross section of a colored particle could be extremely enhanced by non-perturbative effects, which may render the density too small to be detected. Since these effects are not yet understood well quantitatively, large uncertainties of as much as ten orders of magnitude could emerge in the calculation of the relic density [13], making a definite prediction difficult. In addition, some cosmological reasons, such as possible low-energy inflation, could dilute the relic density well below the detectable level. Therefore, definite constraints on the stable particle should come only from accelerator experiments.

In summary, we have presented a new supersymmetric standard model based on $SU(3) \times SU(2) \times U(1) \times U'(1)$ gauge symmetry and $N = 1$ supergravity. In this model, the proton is stable by gauge symmetries without invoking a further symmetry. The right-handed neutrinos are introduced as fields which are to cancel anomalies. After $U'(1)$ symmetry is spontaneously broken, large Majorana masses are induced for the right-handed neutrinos, leading naturally to light neutrinos consistent with experiments. The effective μ parameter is also generated by the symmetry breaking. A natural energy scale of this model is of order 1 TeV, which does not require excessive fine-tuning of parameters for electroweak symmetry breaking. The EDMs of the neutron and the electron can also be accommodated without fine-tuning CP -violating phases.

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TABLES

TABLE I. Particle contents and their quantum numbers.

	SU(3)	SU(2)	U(1)	U'(1)
Q^i	3	2	$\frac{1}{6}$	$\frac{1}{12}$
U^{ci}	3^*	1	$-\frac{2}{3}$	$\frac{1}{12}$
D^{ci}	3^*	1	$\frac{1}{3}$	$\frac{7}{12}$
L^i	1	2	$-\frac{1}{2}$	$\frac{7}{12}$
N^{ci}	1	1	0	$-\frac{5}{12}$
E^{ci}	1	1	1	$\frac{1}{12}$
H_1^i	1	2	$-\frac{1}{2}$	$-\frac{2}{3}$
H_2^i	1	2	$\frac{1}{2}$	$-\frac{1}{6}$
S^i	1	1	0	$\frac{5}{6}$
K^i	3	1	$\frac{1}{3}$	$-\frac{2}{3}$
K^{ci}	3^*	1	$-\frac{1}{3}$	$-\frac{1}{6}$

TABLE II. Parameter values.

g'	$ \lambda_H $	$ B_H m_{3/2} $	$M_{H_1}^2$	$M_{H_2}^2$	M_S^2
0.36	0.10	1.0 TeV	$(1.2 \text{ TeV})^2$	$(0.29 \text{ TeV})^2$	$-(0.71 \text{ TeV})^2$

TABLE III. The v.e.v.s and masses.

v_2/v_1	v_s	M_{Z_2}	R	
5.0	3.4 TeV	1.0 TeV	1.4×10^{-4}	
M_{H^0}			M_{A^0}	M_{H^\pm}
85 GeV	1.0 TeV	1.1 TeV	1.1 TeV	1.1 TeV